

A pairing hypothesis based on resonating valence bond state for hole doped copper oxide high temperature superconductors

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To explain the high-temperature superconductivity of hole-doped copper-oxide high-temperature superconductors (HDCO-HTSCs), Anderson proposed a theory: (A) the pseudogap state is a resonating valence-bond (RVB) state below T^* and (B) the RVB state translates itself into high-temperature superconducting state below T_c . In this paper we abandon Anderson theory B but still retain Anderson theory A and add three new hypotheses. Jointed three hypotheses with Anderson theory A, we construct an effective Hamiltonian of HDCO-HTSCs and explain why T_c -line is a dome in phase diagram and why HDCO-HTSCs have a higher T_c^{max} than that of conventional superconductors.

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I. INTRODUCTION

One experiment [1] shows clearly that Cooper pairs are still carries of high-temperature superconducting state for hole-doped copper-oxide high-temperature superconductors (HDCO-HTSCs). For conventional superconductors, crystal lattice is a background of superconducting state and its collective modes (phonons) provide glue for Cooper pairs. However, the breakthrough of McMillan limit reveals that the glue of Cooper pairs of HDCO-HTSCs is no longer provided by crystal lattice background. If high-temperature superconducting state still need one background to provide glue for its Cooper pairs, what is the kind of background? In this paper we propose this background is a resonating valence-bond (RVB) state [2] which collective modes are glue of Cooper pairs.

The phenomenon [3] that pseudogap coexists with superconducting gap below T_c reveals that RVB state is a background of high-temperature superconducting state. Anderson's RVB theory [2]— pseudogap state is a RVB state— still provides the best explanation for pseudogap phenomenon, in which pseudogap comes from pair-breaking of singlet pair. So pseudogap is a signal of RVB state same as superconducting gap is a signal of superconducting state. The phenomenon that pseudogap coexists with superconducting gap reveals that RVB state coexists with superconducting state and the former is a background of the latter below T_c .

There are two kinds of pictures about the phenomenon that pseudogap coexists with superconducting gap. One is single-gap picture [4–7] and another is two-gap picture [8–13]. Single-gap picture shows that pseudogap is a precursor of superconducting gap, which supports Anderson theory A: the pseudogap state is a RVB state below T^* and simultaneously supports Anderson theory B [14]: below T_c the RVB state translates itself into high-temperature superconducting state in which singlet pairs melt into Cooper pairs. However, two-gap picture shows that pseudogap is different from superconducting gap and Cooper pairs can't come from the melting of singlet pairs, which rejects Anderson theory B but still supports An-

derson theory A. This poses a rather puzzling situation and has been extensively discussed [15].

Since single- and two-gap picture together support Anderson theory A, one way out of the dilemma is to abandon Anderson theory B but still to retain Anderson theory A and to add new hypotheses. In this paper, we add three new hypotheses as following: (1) RVB state is a background of high-temperature superconducting state. (2) The RVB background possesses low-energy collective excitation modes which are glue of Cooper pairs. (3) Cooper pairs don't come from the melting of singlet pairs but have other origin. Based on above three hypotheses and Anderson theory A, we construct an effective Hamiltonian of HDCO-HTSCs, and from this we deduce a functional relation between T_c and doping concentration x .

It always needs to introduce some new concepts to build a new theory. In this paper we introduce three new concepts as following: (1) "RVB-background", i.e. RVB state, which is a background of high-temperature superconducting state. (2) "Rubions", collective modes of RVB-background, which are glue of Cooper pairs. (3) "free- d -electrons", electrons that make up Cooper pairs, which come from the evolving of the $d_{x^2-y^2}$ electrons in process of hole-doping.

This paper is organized as follows. In Sec.II three new hypotheses are presented in details. In Sec.III we construct an effective Hamiltonian of HDCO-HTSCs. In Sec.IV we calculate T_c and explain the cause of high critical temperature T_c^{max} based on effective Hamiltonian. Finally, in Sec.V, we discuss four questions: (A) What is the rubion? (B) What does define high temperature superconductivity? (C) How to achieve a room temperature superconductor? (D) How to prove our theory false?

II. HYPOTHESES

A. RVB state is only a background

One recent experiment [16] shows that pseudogap phase is not a crossover region but an independent phase

precisely linked with T^* . Another recent experiment [17] indicates that onset of pseudogap phase is abrupt when temperature traverses T^* . Above two experiments together imply that a phase-transition takes place at T^* and a new electronic state hides itself in the pseudogap phase. We think this new electronic state is just RVB state and T^* is a critical temperature of RVB phase. And above two experiments also imply that Anderson theory A, the pseudogap state is a RVB state, is reasonable.

The picture that RVB state coexists with high-temperature superconducting state is supported strongly by that pseudogap exists clearly in the overdoped region [18]. If two states coexist, it means that one state lies likely in bottom and becomes a background of another state. We suppose that RVB state is located at bottom and is a background of superconducting state below T_c . Thus, high-temperature superconducting state has two backgrounds: one is crystal lattice background and another is the RVB background.

The hypothesis of RVB background can explain following experimental observation. One group, led by Zheng [19], found pseudogap still exists in the $T \rightarrow 0$ limit when a strong magnetic field destroys high-temperature superconducting state. According to Anderson theory A, pseudogap is a signal of RVB state existence. If RVB state is a background of superconducting state below T_c , it can explain Zheng's experimental observation.

B. The RVB background possesses collective modes

According to Goldstone theorem, if continuous symmetries are broken, system will possess a zero-mass Goldstone mode. The crystal lattice background breaks continuous translational and rotational symmetries in real-space, so it possesses phonon, which is glue of conventional superconductors. If RVB state is another background of high-temperature superconducting state, whether does it also break continuous symmetries and possess a zero-mass Goldstone mode to provide glue for HDCO-HTSCs?

One group, led by Davis [1], looked into the behavior of electrons of an underdoped cuprate in real- (r-) and in reciprocal space simultaneously by scanning tunneling microscopy; they found that the pseudogap excitations, locally at atomic scale, are r-space excitations that lack the delocalized characteristics. The fact that pseudogap excitations lack the delocalized characteristics reveals RVB state is a valence-bond solid of r-space, and same idea is holden by Han *et al.* [20].

If RVB state is a valence-bond solid of r-space, it will break continuous translational and rotational symmetries in r-space. Breaking of continuous symmetries leads to the emergence of a zero-mass Goldstone mode according to Goldstone Theorem. We name the zero-mass Goldstone mode as "rubion". And since the rubion is massless, it can induce long-range interaction and serve as the

glue of HDCO-HTSCs.

The hypothesis of rubion can explain an experimental observation. One group, led by Taillefer [21], found a nonzero thermal conductivity for underdoped $YBa_2Cu_3O_y$ in the $T \rightarrow 0$ limit. It was attributed by Taillefer's group to a contribution of a new boson mode. If rubion is just the new boson mode, it can explain Taillefer's experimental observation.

Through exchanging a rubion, two nonlocalized electrons are stucked into one Cooper pair; if this story is true, where do the two nonlocalized electrons come from?

C. The nonlocalized electrons which make up Cooper pairs come from the evolving of the $d_{x^2-y^2}$ electrons

To explain the origin of Cooper pairs, Anderson theory B [14] proposed that RVB state translates itself into high-temperature superconducting state when cuprates are doped so sufficiently that singlet pairs melt into Cooper pairs. However, the proposal that Cooper pairs come from singlet pairs is rejected by two-gap picture and further rejected by Zheng's experiment [19]: when a strong magnetic field destroys high-temperature superconducting state, pseudogaps still exist in the $T \rightarrow 0$ limit. The existence of pseudogaps shows singlet pairs still exist when Cooper pairs is killed by a strong magnetic field. Zheng's experiment is not in conflict with Anderson theory A (RVB theory) but shows that it is unlikely that Cooper pairs come from the melting of singlet pairs and Anderson theory B must be abandoned. We need to find a new origin about Cooper pairs.

Copper-oxide plane is a conducting layer and $d_{x^2-y^2}$ electrons of copper site are responsible for the superconductivity. According to Anderson theory A, RVB state seems to be participated by all $d_{x^2-y^2}$ electrons (for short, d electrons). If retains Anderson theory A, on the copper-oxide plane what else electrons make up Cooper pairs?

In this paper, Anderson theory A is improved by us as following: pseudogap state is a RVB state but it is not all d electrons to participate in RVB state due to hole dopant. In hole-doping process, holes don't enter into copper sites but into oxygen sites. We think that hole-doping of oxygen sites makes d electrons of copper sites evolve into two categories: one category participating in RVB state at the T^* and another evolving into Cooper pairs at the T_c , i.e. it is not all d electrons to participate in RVB state.

Why in the hole-doping process d electrons don't totally participate in RVB state but evolve into two categories? (1) RVB state is a linear superposition of singlet pairs and the onset of one singlet pair needs a vital condition that is the superexchange (or Kramers-Anderson superexchange [22]). (2) Oxygen ions are nonmagnetic in copper-oxide plane and nonmagnetic oxygen ions are superexchange media of singlet pair. A hole enters into an

oxygen site to make a nonmagnetic oxygen ion become a magnetic oxygen ion; it means that a superexchange medium is destroyed and a singlet pair is broken up and two d electrons are set free. (3) The more holes are doped into oxygen site, the more superexchange media are destroyed, and the more d electrons are free outside from RVB state, which are named as “free- d -electrons” by us. These free- d -electrons are just the original electrons which make up Cooper pairs.

The hypothesis of free- d -electrons can explain following two experiments: (1) One group, led by Sun [23], found that delocalized fermions exist in underdoped $YBa_2Cu_3O_y$. If these delocalized fermions are just our assumed free- d -electrons, it can explain Sun’s experimental observation. (2) Another group, led by Taillefer [24], measured quantum oscillations in an underdoped cuprate. They found that the quantum oscillation signals occurring in a Hall resistance which has a negative sign. The Hall coefficient is expected to be positive according to conventional ideas (holes are thought as carries of HDCO-HTSCs). However, the Hall coefficient is negative in Taillefer’s experimental observations. It means that the carries of HDCO-HTSCs are likely electrons instead of the holes. The hypothesis of free- d -electrons can explain Taillefer’s experimental observations.

The dualism hypothesis that d electrons evolve into RVB state and free- d -electrons in the hole-doping process can also explain following two properties of HDCO-HTSCs: rare carries and peculiar Fermi surface topology. The cause of rare carries is that most d electrons participate in RVB state while a few d electrons evolve into free- d -electrons in hole doping process. Recently, Hu and Ding [25] proposed that the key ingredients in the determination of high T_c and pairing symmetries are local antiferromagnetic interactions in r -space and Fermi surface topology in reciprocal space. The peculiar Fermi surface topology can be explained by the dualism hypothesis if we further suppose that free- d -electrons lie in the Fermi arc/pocket [26] while these electrons participating in RVB state lies in antinode region in reciprocal space. In addition, the local antiferromagnetic interactions can be explained by RVB state due to the superposition of singlet pairs. As for d -wave pairing symmetry, we think that needs to find its clue from copper oxide parent compounds in which a remnant Fermi surface shows a d -wave-like dispersion [27].

III. HAMILTONIAN

We can construct an effective Hamiltonian of HDCO-HTSCs based on above three hypotheses—rubion, RVB background and free- d -electrons. When one free- d -electron goes through the RVB background, it causes a deformation of RVB background, i.e. one free- d -electron emits a rubion. When another free- d -electron walks into the deformed region, it feels an attraction, i.e. another free- d -electron absorbs a rubion. Above process can be

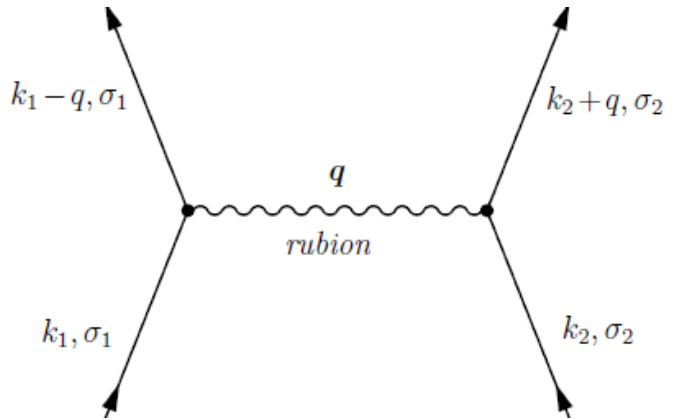


FIG. 1: Rubion-induced electron-electron interaction. The k_1, σ_1 is the first free- d -electron which becomes $k_1 - q, \sigma_1$ after emits a rubion q , and the k_2, σ_2 is the second free- d -electron which becomes $k_2 + q, \sigma_2$ when absorbs a rubion q . Through media of a rubion q , two free- d -electron build up an attractive interaction.

clarified by a Feynman Diagram as Fig. 1. This process is not a direct Coulomb interaction but a rubion-induced electron-electron attractive interaction which can be presented by following formula

$$H_{rubion} = \frac{1}{2} \sum_{q, k_1, k_2, \sigma_1, \sigma_2} R_{k_1, k_2, q} C_{k_1 - q, \sigma_1}^\dagger C_{k_2 + q, \sigma_2}^\dagger C_{k_2, \sigma_2} C_{k_1, \sigma_1}, \quad (1)$$

where $R_{k_1, k_2, q}$ is a rubion-induced attractive potential and q represents a rubion.

In addition, there is a direct Coulomb interaction between two free- d -electrons. According to Quantum Electrodynamics, this direct Coulomb interaction should be presented by exchanging photon between two free- d -electrons. However, because of Coulomb screen of RVB state (most $d_{x^2-y^2}$ electrons participate in RVB state), the direct Coulomb interaction between two free- d -electrons can be presented by an effective interaction,

$$H_{coul} = \frac{1}{2} \sum_{q, k_1, k_2, \sigma_1, \sigma_2} U_{k_1, k_2, q} C_{k_1 - q, \sigma_1}^\dagger C_{k_2 + q, \sigma_2}^\dagger C_{k_2, \sigma_2} C_{k_1, \sigma_1}, \quad (2)$$

where $U_{k_1, k_2, q}$ is a RVB Coulomb screening repulsive potential and q still represents a rubion.

Combining above two interaction, the effective Hamiltonian of HDCO-HTSCs is written as

$$H = H_{rubion} + H_{coul}. \quad (3)$$

If rubion-induced attractive potential $R_{k_1, k_2, q}$ is greater than the RVB Coulomb screening repulsive potential $U_{k_1, k_2, q}$, then $R_{k_1, k_2, q} + U_{k_1, k_2, q}$ will be a net attractive potential and two free- d -electrons can be stucked into one Cooper pair.

According to formula (3), if only considering those interactions which scatter a pair of free- d -electrons of opposite momentum and spin ($k \uparrow, k \downarrow$) to another pair state

$(k' \uparrow, k' \downarrow)$, the interactions take the simplified form:

$$H_{rubion} = \frac{1}{2} \sum_{kk'} R(k - k') C_{k'}^\dagger C_{-k'}^\dagger C_{-k} C_k, \quad (4)$$

$$H_{coul} = \frac{1}{2} \sum_{kk'} U(k - k') C_{k'}^\dagger C_{-k'}^\dagger C_{-k} C_k. \quad (5)$$

On the Fermi arc/pocket of reciprocal space, we can introduce an averaged strength for the net electron-electron interaction,

$$-V = \langle -R(k - k') + U(k - k') \rangle_{Av}, \quad (6)$$

where V is positive and has a d -wave symmetry [28] and the average is to be carried out over all free- d -electrons on the Fermi arc/pocket of reciprocal space. With the help of V , formula (3), can be presented as

$$H = - \sum_{kk' \in \text{arc/pocket}} V C_{k'}^\dagger C_{-k'}^\dagger C_{-k} C_k. \quad (7)$$

Formula (7) is the effective Hamiltonian of HDCO-HTSCs.

IV. APPLICATIONS

A. Calculation of T_c in underdoping region

From formula (7), we can find out that the effective Hamiltonian of HDCO-HTSCs is still a BCS-like Hamiltonian, in which the only difference is that V represents the electron-rubion interaction instead of electron-phonon interaction.

With the aid of V , we can define the energy gap,

$$\Delta = V \sum_k \langle C_{-k} C_k \rangle, \quad (8)$$

$$\Delta^* = V \sum_k \langle C_{-k}^\dagger C_k^\dagger \rangle, \quad (9)$$

where both $\langle C_{-k} C_k \rangle$ and $\langle C_{-k}^\dagger C_k^\dagger \rangle$ are pair operator and the average is to be carried out over superconducting ground state which is a distribution of Cooper pairs on the Fermi arc/pocket of reciprocal space.

An experimental group, lead by Wen [29], shows that the weak-coupling d -wave BCS universal relation,

$$\Delta_0 = 2.14 k_B T_c, \quad (10)$$

still exists in HDCO-HTSCs and even in overdoped region. It reveals that the rubion-induced electron-electron interaction is still a weak-coupling interaction. It means the weak-coupling approximation, $N_0 V \ll 1$, can be used for following deducing process.

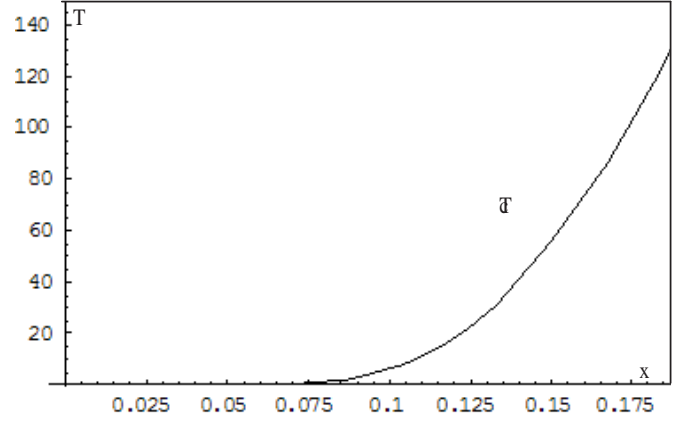


FIG. 2: T_c as a function of doping concentration x according to function relation $T_c = 0.93 \Theta_D \exp(-\frac{1}{V\alpha x})$, which is derived from the effective Hamiltonian of HDCO-HTSCs. Θ_D is set as $5 \times 10^3 K$, α as 15, and V as 0.1. The trend of T_c -line in underdoping region is consistent with that of the phase diagram of HDCO-HTSCs.

Under the weak-coupling approximation, starting from formula (8, 9) and repeating same deducing procedure as weak-coupling BCS theory [30], we obtain an expression of high-temperature superconducting energy gap in $T = 0K$ as following

$$\Delta_0 = 2 \hbar \omega_D \exp[-1/N_0 V], \quad (11)$$

where ω_D is Debye frequency of rubions and N_0 is the energy state density of free- d -electrons on the Fermi arc/pocket. For HDCO-HTSCs, Δ_0 is $10^{-2} eV$ magnitude according to experimental data [3]. If we set $N_0 V$ as 0.1 based on the weak-coupling limit $N_0 V \ll 1$, then the Debye temperature Θ_D ($\Theta_D = \hbar \omega_D / k_B$) of rubions is equal to $10^3 K$ magnitude approximately.

Comparing formula (10) with (11), we obtain the T_c expression of HDCO-HTSCs as following

$$T_c = 0.93 \Theta_D \exp(-1/N_0 V), \quad (12)$$

Further, according to the hypothesis which free- d -electrons are induced by hole-doping process, the N_0 should be proportional to hole-doping concentration x , i.e. $N_0 = \alpha x$ where α is scale factor. In formula (12), substituting N_0 with αx , we can obtain a functional relation between T_c and x as following

$$T_c = 0.93 \Theta_D \exp(-\frac{1}{V\alpha x}), \quad (13)$$

where $V\alpha x \ll 1$ is required by the weak-coupling limit. Based on formula (13), the function plots in underdoping region is presented as Fig. 2 in which the trend of T_c -line is consistent with that of the phase diagram of HDCO-HTSCs.

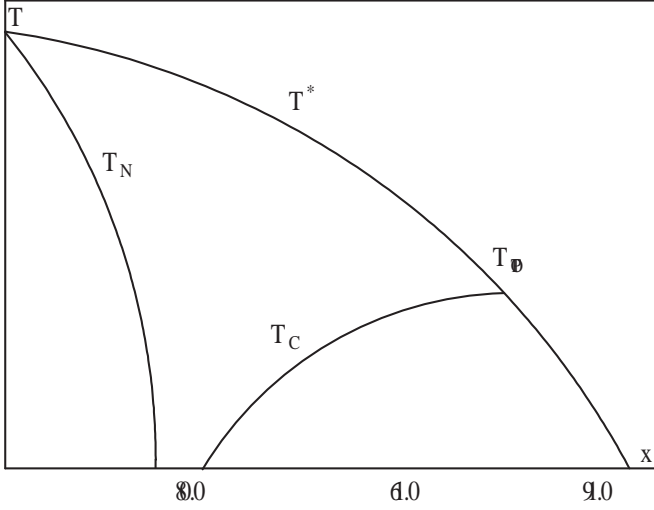


FIG. 3: Rubion hypothesis predicts that the optimal dopant point is located at the meeting point of T_c -line and T^* -line. After the optimal dopant point, T_c -line blends into T^* -line and together extend to $x = 0.19$ where an experiment [31] shows that pseudogap only exists under this doping concentration.

B. Explanation for that T_c -line is a dome

In phase diagram of HDCO-HTSCs, T^* -line reflects an abilities of RVB state withstanding thermal-fluctuation. The ability is gradually weakened by quantum fluctuation which is imported by hole-dopant. So, T^* -line stretches inevitably towards lower right of phase diagram. On the other hand T_c -line reflects phase stiffness of high-temperature superconducting state and T_c is in proportion to concentration of Cooper pairs. Based on the free- d -electron hypothesis, the more holes are doped, the more free- d -electrons are free out. It means the more Cooper pairs are made up and the stronger phase stiffness is owned by high-temperature superconducting state with increasing hole-doping concentration. So T_c -line stretches inevitably towards the upper right of phase diagram until meets T^* -line.

Based on the rubion hypothesis, RVB state is a precondition of high-temperature superconducting state. Once RVB state is ruined by the thermal fluctuation, high-temperature superconducting state collapses instantly because that glue of the latter is provided by the collective modes of the former. The collapse of RVB state means high-temperature superconducting state to lose its glue. The thermal fluctuation must firstly ruin RVB state, after that, destroying high-temperature superconducting state; so, after the meeting point, T_c -line blends inevitably into T^* -line and T_c -line cannot be anything but a dome. Rubion hypothesis predicts the optimal dopant point is located at the meeting point of T_c -line and T^* -line (see Fig. 3).

That RVB state is a precondition of high-temperature

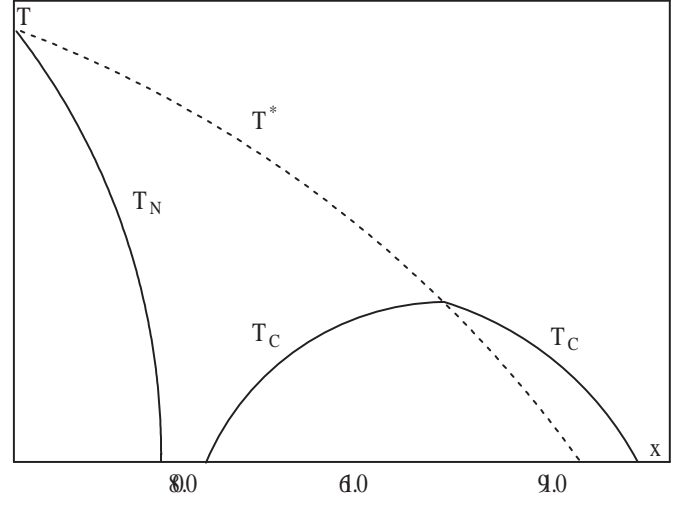


FIG. 4: Rubion hypothesis rules out a possibility that Fig. 4 is as an universal phase diagram. Fig. 4 comes from Fischer [32] *et al.* The character that rubion hypothesis rules out the phase diagram Fig. 4 also predicts that there isn't Nernst effect existing above T_c -line in overdoping region.

superconducting state means the T^* -line is a precondition of T_c -line, which rules out the phase diagram Fig. 4 as an universal phase diagram.

C. Cause of high critical temperature T_c^{max}

Since Wen's experiment [29] reveals that the carriers of HDCO-HTSCs are weak-coupling Cooper pairs, even if rubion is the glue of Cooper pair, the rubion-induced electron-electron interaction is not more prominent than the phonon-induced electron-electron interaction. Why does rubion-induce high-temperature superconducting state have a higher critical temperature T_c^{max} at optimal dopant point than that of conventional superconductors?

For conventional superconductors, the glue of Cooper pairs comes from phonon-induced electron-electron attracting interaction which is achieved through an electron-induced local distortion of crystal lattice background. With temperature arising, thermal fluctuation increasingly smoothes the local distortion of crystal lattice background and then Cooper pairs lose their glue. So it is impossible that the T_c of conventional superconductors breaks through McMillan limit.

For HDCO-HTSCs, superconducting state has two backgrounds: one is crystal lattice background and another is the RVB background. The glue of Cooper pairs comes from rubion-induced electron-electron attracting interaction which is achieved through a free- d -electron-induced local distortion of RVB background. If thermal fluctuation wants to break up rubion-induced Cooper pairs, it must take two steps: firstly thermal fluctuation perturbs crystal lattice background, and secondly,

through scattering interaction of crystal lattice background, perturbs the RVB background; the perturbation of RVB background will smooth free- d -electron-induced local distortion of RVB background and then Cooper pairs lose their glue.

Since it needs two steps that thermal fluctuation breaks up Cooper pairs, the pair-breaking of rubion-induced Cooper pairs is a high order effect of thermal fluctuation. So, it is not an easy task that thermal fluctuation causes rubion-induced Cooper pairs losing their glue through the way that thermal fluctuation perturbs the RVB background. The easiest way is that the thermal fluctuation destroy RVB background directly and then rubion-binding Cooper pairs lose their glue. For HDCO-HTSCs, at optimal dopant point a high T_c^{max} does not mean that superconducting state needs a more sticky glue to bind Cooper pair. The key of high T_c^{max} is the thermal fluctuation must firstly destroy RVB state, after that, destroying high-temperature superconducting state. As a result, the high T_c^{max} depends on the high critical temperature T^* at optimal dopant point.

V. DISCUSSIONS

A. What is the rubion?

In a paper [33] and at its last two paragraphs, Anderson said: “But especially if it (RVB) is a Bose state, it will probably have low-energy excitations...”. Anderson’s words imply that RVB state is a Bose state; since high-temperature superconducting state is also a Bose state, we don’t take into account the spin-interaction between Cooper pairs and RVB singlet pairs in the effective Hamiltonian of HDCO-HTSCs. Anderson’s words also imply that RVB state possesses not only a high-energy single-particle excitation, pseudogap, but also a low-energy collective excitation which is just the rubion proposed by us.

Then what is the rubion? First, rubion can not be a plasmon because plasmon is a collective excited mode of wide-band metal while HDCO-HTSCs are narrow-band bad-metals. Second, rubion can not be a spin wave because spin wave is a Goldstone mode of ferromagnetism or antiferromagnetism while RVB state recover spin rotation symmetry when hole-dopant process kills antiferromagnetism of parent compound. So rubion is a new low-energy collective excited mode.

If rubion is a new collective mode, what is the properties of rubion? According to Goldstone theorem, rubion is a Goldstone mode when the continuous translational and rotational symmetry of RVB state is broken by short-range correlations. As a Goldstone mode, rubion ought to be a spinless boson of zero mass. As a quantum of collective mode, rubion ought to possess an energy $\hbar\omega$, where ω is frequency of new collective mode. Rubion also ought to contribute a thermal conductivity to HDCO-HTSCs and its Debye temperature is equal to

$10^3 K$ magnitude approximately according to the calculation of section Applications.

Taillefer’s experiment [21] found a nonzero thermal conductivity for underdoped $YBa_2Cu_3O_y$ in the $T \rightarrow 0$ limit, which was attributed by Taillefer’s group to a contribution of a new boson mode. If rubion is just the new boson mode, Taillefer’s experiment can determine the dispersion relation $\omega = \omega(q)$ of rubion.

B. What defines high temperature superconductivity?

Through the rubion hypothesis, RVB state produces a correlation with high-temperature superconducting state, in which the former provides glue with Cooper pairs of the latter. Due to existence of RVB state, the perturbation of superconducting state is a high order effect of thermal fluctuation. The thermal fluctuation must firstly destroy RVB state, after that, destroying high-temperature superconducting state. In a sense, the RVB state itself becomes a shock-absorber of high-temperature superconducting state.

For conventional superconductors, the crystal lattice background only provides glue with superconducting state. However, for HDCO-HTSCs, there is a interlayer between superconducting state and crystal lattice background, and the interlayer is just RVB state which provides not only glue but also shock-absorber with high-temperature superconducting state. So, about the question: “What does define high temperature superconductivity? [34]”, our answer is as following: that the RVB state simultaneously providing glue and shock-absorber with superconducting state, defines high temperature superconductivity.

C. How to achieve a room temperature superconductor?

Since the T_c^{max} is equal to T^* at optimal dopant point, the key of high T_c^{max} doesn’t lie in the viscosity of glue but in the stability of RVB background. On the face of things, T_c^{max} reflects phase stiffness of high-temperature superconducting state at optimal dopant point. Well actually, T_c^{max} reflects an ability that RVB state withstands thermal fluctuation at optimal dopant point. Maybe we can hold T_c^{max} up to room temperature if we adopt following two ways.

One way is to find a cuprate which T^* -line owns a higher whole height. The T^* -line is a precondition of T_c -line and the latter always meets the former at optimal dopant point (see Fig. 3). If T^* -line own a higher whole height, the optimal dopant point will own a higher position when T_c -line meets T^* -line. To increase whole height of T^* -line may be a good way to promote T_c^{max} up to room temperature.

Another way is maintaining the RVB background stable to the greatest extent. The hydrostatic pressure is still the best approach to maintain the RVB background stable and to achieve a higher T_c^{max} because it brings about two benefits for improvement of T_c^{max} . One benefit is increase of holes caused by oxygen ordering effects [35]. The increase of holes means that the superexchange media decrease and the more d -electrons free out of RVB state and the more Cooper pairs make up, and then phase stiffness strengthens and T_c^{max} ascends. Another benefit is the superexchange interaction J increasing caused by hydrostatic pressure [36]. At the optimal dopant point, the increase of J means RVB state becomes more and more stable so that the thermal fluctuation caused by the ascended T_c^{max} can further be endured by the RVB background. Similarly multi-layer planes under hydrostatic pressure may further reinforce the stability of RVB background due to the coupling between layers. Unfortunately, the hydrostatic pressure also brings about an unfavorable factor to the RVB background because the hydrostatic pressure increases buckling angle of copper-oxide planes so that RVB state collapses easily [37]. Avoiding the buckling under a high hydrostatic pressure may be another good way to achieve room temperature superconductor.

If we try our best to find a cuprate which T^* -line owns the highest whole height and manage to avoid the buckling under a superhigh hydrostatic pressure some day, a room temperature superconductor may no longer be a dream.

D. How to prove our theory false?

According to the proposal of Karl Popper, if a theory belongs to science, it must own a possibility that is proved to be false. The character that rubion hypothesis

rules out the phase diagram Fig. 4 means that experimental scientists can design an experiment to check the falsifiability of our theory. This is an experiment based on Nernst effect because the Nernst effect can reflect the existing range of Cooper pair [38–40]. Since T^* -line is precondition of Cooper pairs according to rubion hypothesis, it is impossible that Nernst effect exists above T^* -line. Before the optimal dopant point, the T^* -line has a higher position than that of T_c -line, which allows superconducting phase fluctuation existing between T_c -line and T^* -line so that the Nernst effect can exist above T_c -line of underdoping region. After the optimal dopant point, it is impossible that the Nernst effect exists above T_c -line because the T_c -line blends in T^* -line and the latter is precondition of Cooper pair. In other words, above T_c -line of overdoping region, there are not superconducting phase fluctuation and Nernst effect. If experimental scientists design an experiment to find out Nernst effect existing above T_c -line in overdoping region, it will prove our theory false.

Recently, Taillefer's experiment [41] shows that there is a controversy about the range of Nernst effect in underdoping region, but the controversial range is all luckily under the T^* -line. For overdoping region, there are too few experimental data and too much controversy such as a recent experiment [18] gives a different pseudogap evolution in overdoping region. Rubion hypothesis predicts that the T_c -line meets the T^* -line in overdoping region and there isn't Nernst effect existing above T_c -line in overdoping region. Our theory will further stimulate experimental scientists to pay close attention to overdoping region.

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